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October 1976



**PERFORMANCE CHARACTERISTICS OF A DIESEL ENGINE
USING LOW- AND MEDIUM-ENERGY GASES AS
A FUEL SUPPLEMENT (FUMIGATION)**

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MODULAR INTEGRATED UTILITY SYSTEMS
improving community utility services by supplying
electricity, heating, cooling, and water/ processing
liquid and solid wastes/ conserving energy and
natural resources/ minimizing environmental impact



**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058**

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16. Abstract <p>This report describes a test program conducted to investigate the use of low- and medium-energy gases derived from solid waste. Gases that simulate those gases that could be derived from refuse were injected into the air inlet of a 298-kilowatt (400 horsepower) diesel engine as a fuel supplement. This process is called fumigation. Three different gases with thermal-energy contents of 6.11 MJ/m^3 (164 Btu/ft^3), 18.1 MJ/m^3 (485 Btu/ft^3), and 18.8 MJ/m^3 (505 Btu/ft^3), respectively, were used at rates ranging as high as 20 percent of the normal fuel-oil energy at four different engine load points. The test results indicated approximately 100-percent gas energy utilization with no observable deleterious effect on the engine.</p>			
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A FUEL SUPPLEMENT (FUMIGATION)**

**Leo G. Monford
Lyndon B. Johnson Space Center
Houston, Texas 77058**

PREFACE

The Department of Housing and Urban Development (HUD) is conducting the Modular Integrated Utility System (MIUS) Program devoted to development and demonstration of the technical, economic, and institutional advantages of integrating the systems for providing all or several of the utility services for a community. The utility services include electric power, heating and cooling, potable water, liquid-waste treatment, and solid-waste management. The objective of the MIUS concept is to provide the desired utility services consistent with reduced use of critical natural resources, protection of the environment, and minimized cost. The program goal is to foster, by effective development and demonstration, early implementation of the integrated utility system concept by the organization, private or public, selected by a given community to provide its utilities.

Under HUD direction, several agencies are participating in the HUD-MIUS Program, including the Atomic Energy Commission, the Department of Defense, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Bureau of Standards (NBS). The National Academy of Engineering is providing an independent assessment of the program.

This publication is one of a series developed under the HUD-MIUS Program and is intended to further a particular aspect of the program goals.

COORDINATED TECHNICAL REVIEW

Drafts of technical documents are reviewed by the agencies participating in the HUD-MIUS Program. Comments are assembled by the NBS Team, HUD-MIUS Project, into a Coordinated Technical Review. The draft of this publication received such a review and all comments were resolved.

CONTENTS

Section	Page
SUMMARY	1
INTRODUCTION	1
GENERAL DESCRIPTION	2
TEST OBJECTIVES AND PROCEDURES	3
FUEL PROPERTIES	4
ENGINE TEST PERFORMANCE	5
ERROR ANALYSIS	5
DISCUSSION AND RECOMMENDATIONS	6
REFERENCES	7

TABLES

Table	Page
I CHARACTERISTICS OF DIESEL FUEL (EXXON)	8
II HEATING PROPERTIES OF FUEL GASES	8
III TEST GAS PROPERTIES	9
IV GAS CONSTANTS	10
V AVERAGE UTILIZATION EFFICIENCY	11

FIGURES

Figure	Page
1 Barber-Colman pyrolysis process schematic	12
2 Hamilton-Standard fixed-bed gasifier schematic	12
3 Throttle position as a function of load	13
4 Diesel-fuel consumption test schematic	14
5 Fumigation test schematic	14
6 Diesel-fuel reduction as opposed to gas energy at 230 kilowatts	15
7 Detonation and operating pressure testing diagram	15
8 Cylinder-pressure variation for gas 1 at 230 kilowatts	16

PERFORMANCE CHARACTERISTICS OF A DIESEL ENGINE
USING LOW- AND MEDIUM-ENERGY GASES AS
A FUEL SUPPLEMENT (FUMIGATION)

By Leo G. Monford
Lyndon B. Johnson Space Center

SUMMARY

Of the present methods for extracting energy from refuse, pyrolysis appears promising for energy-related benefits because of the possibility of using the gases produced in this type process as an alternate fuel in internal-combustion engines. A test program was conducted to determine the feasibility of low- and medium-energy gas injection (fumigation) in the air intake of a diesel engine. Such an approach enables close coupling of systems and thus eliminates the need for gas heat value upgrading or compression. Three different premixed gases (two, pyrolysis; one, anaerobic digestor) simulating those that could be derived from refuse were investigated. The amount of each gas required to reduce diesel-fuel consumption by 5, 10, 15, and 20 percent was determined at each of four engine load points. These tests have shown that, without major modification, many existing engines can very efficiently utilize low-energy gas generated from solid waste for as much as 20 percent of the normal fuel consumption. Combustion pressures were recorded during the testing, but no detrimental effects on the engine were observed.

INTRODUCTION

The NASA, together with other government agencies, is conducting the Modular Integrated Utility System (MIUS) Program sponsored by the Department of Housing and Urban Development. The MIUS concept combines the utility services of electrical power, heating and cooling, water supply and wastewater treatment, and solid-waste management into a single local plant, with attendant conservation of energy. The objective of the MIUS project is to demonstrate the technical and economic feasibility of this concept.

The Lyndon B. Johnson Space Center has been conducting studies on the application of advanced technology in commercial housing, with the objectives of conserving natural resources, abating pollution, improving construction, and increasing household safety. These studies involve the investigation of various types of hardware in the MIUS that provide (onsite) all the usual utilities and services generally obtained through conventional means. Building systems designs are first configured and analyzed by computer; then, the

optimized sizing of various arrangements is evaluated in the MIUS integration and subsystems test (MIST) facility.

In these studies, solid-waste incineration has been used to recover energy in the form of heat from the refuse. This energy is used to supplement space-conditioning requirements. Burn times may be adjusted to coincide with peak demand periods, with limited refuse storage capability. During off-seasons, additional heat is not needed; therefore, the energy-related benefits of incineration are eliminated, and approximately 50 percent of the recovered trash energy is utilized.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

GENERAL DESCRIPTION

Pyrolysis is another method of solid-waste energy extraction that has been demonstrated. In the solid-waste pyrolysis process, fuel gas is produced by thermal decomposition of refuse in the absence of oxygen. The gas thus produced can then be burned for heat when needed or, hopefully, for the generation of electrical energy by injecting the gas into the air inlet of a diesel engine to supplement the diesel-fuel requirements. For a natural-gas-burning engine, the gases would be mixed. Two example techniques for producing gas considered acceptable for the fumigation process are shown in figures 1 and 2. (Techniques that produce suitable fumigation gas are not limited to these types.) The first process, designed and tested by the Barber-Colman Company, produces a medium-energy gas (ref. 1). The Hamilton-Standard Division of United Aircraft Corporation has refined an air-gasification technique that generates low-energy gas (ref. 2). A test series performed by Hamilton-Standard was the only previous fumigation attempt that could be located. The gas mixtures used in their testing were pyrolysis-derived; however, their engine was an open-combustion-chamber engine that used the injected gas at an efficiency of approximately 50 percent. Gas utilization efficiency is defined as the quantity of diesel-fuel energy saved divided by the amount of gas energy injected to produce this savings.

The purpose of this report is to summarize the results of a short-term test program conducted to determine the potential energy-related benefits associated with the fumigation of low-energy gases and the possible short-term effects on the engine. Test techniques and results are presented in summary form. Tests of much longer duration and the use of gases actually derived from candidate processes would be required for meaningful long-term engine effects analysis and operating efficiencies.

The test program was conducted using the MIST test engine (Caterpillar D-353), which is a four-stroke, in-line, six-cylinder, turbocharged, after-cooled diesel engine that operates at a constant 1200 rpm. The engine is used

to drive a three-phase, 60-hertz, brush-type generator rated at 375 kilovolt-amperes. Loads of as much as 100 percent may be applied with a variable water-bath load bank that provides three-phase electrical loading by insertion of metal probes into a water tank. The Caterpillar diesel engine is a precombustion, or divided combustion chamber, design. In this type unit, peak combustion pressures are controlled to a level only slightly higher than compression pressure.

The performance of a diesel engine is controlled by design, operating conditions, and fuel. The design is fixed; so, for a given set of operating conditions, variation in fuel characteristics and consumption would be due to a modified combustion process. Fumigation testing was conducted, therefore, by fixing all performance-relevant criteria at various levels and then repeating the same levels, etc., with gaseous fuel injection to supplement diesel oil. Results could then be obtained by comparing total fuel consumptions.

TEST OBJECTIVES AND PROCEDURES

The primary objectives of this test series were to determine gas utilization efficiency and to evaluate engine performance at various loads using three different gas mixtures. A fuel-rack position sensor was installed to accurately fix the percentage of fuel requirement supplied by the injected gas. The output of this sensor was then electrically conditioned to provide an output linear with respect to diesel-fuel rate. It was determined through testing that fuel rate is linearly proportional to the engine load. The relationship between these variables is shown in figure 3, which is based on data collected throughout both test series.

To provide direct readout of fuel rate on a digital meter, a sensor calibration procedure was established. With the engine "off," the fuel rack was first set at the mechanical stop corresponding to minimum fuel rate. The sensor output voltage was then nulled electronically to read 0 volt. The fuel rack was then positioned for maximum fuel input, and the output voltage level was adjusted to 10 volts with gain control. The rack was then manually positioned to produce an output of 2.17 volts (fig. 3). At this location, the projected fuel-rate curve crosses the zero fuel point; so the null was reset for 0 volt. To complete the procedure, the rack was again brought to maximum and the gain was adjusted to produce 1.310 volts (corresponding to 59.42 kg/hr (131.0 lb/hr)). The amount of diesel fuel consumed per hour at various fixed loads was accurately determined by using a small test tank with a calibrated sight glass (fig. 4). The test-tank sight gage used to determine diesel-fuel usage has a resolution of 10.73 divisions per 0.004 cubic meter (1 gallon) of fuel. Each division is approximately 1.27 centimeters (0.5 inch) long and represents 0.2975 kilogram (0.6558 pound) of fuel. The valves were arranged such that the test tank could be filled from fuel storage in the same manner as the day tank. This arrangement was used in lieu of a fixed fuel volume or a fuel-weighing system so that a test duration of 5 minutes could be used independently of engine load. The fumigation test schematic for gas injection is shown in figure 5. This system consisted primarily of a gas-bottle manifold and a flow-control mechanism. As many as five bottles could be connected to

provide gas quantities required by these tests. The gas-injection system provided a fuel source not automatically controlled by protective engine circuitry. The MIST engine has automatic air shutoff on overspeed, but all other control parameters operate to stop fuel supply. The electronic system used to provide fuel-rate indication also incorporated an adjustable low-limit controller that activated a gas shutoff solenoid if a failure caused an automatic diesel-fuel shutdown. Without this safeguard, the engine could have continued to run on gas energy alone and could have caused overspeeds at very low loads.

With the engine loaded at a constant electrical output, sufficient time was allowed for operating temperatures to stabilize before gas injection. Periodic checks of diesel-fuel consumption without fumigation were conducted to provide repeatability data and to determine sensitivity to ambient temperatures, humidity, etc. (The data were very repeatable during this test, so this type of data is not included.) After temperature stabilization at a constant load, gas was injected into the air intake of the engine. Initially, a flowmeter was used to adjust and maintain gas flow rates. It was found that gas flow could be adjusted more accurately by observing the diesel-fuel rate decline on the rack position meter to obtain the desired percentage reduction; thus, flow rate was held constant during the test period by this method. Bottle pressures and temperatures were taken before and after testing. The actual amount of gas used in a given test was then calculated on the basis of these values. In this manner, two separate series of tests were completed for each of the three gases. Each series consisted of a 5-, 10-, 15-, or 20-percent diesel-fuel reduction at electrical load points of 60, 100, 150, or 230 kilowatts during more than 100 5-minute runs.

FUEL PROPERTIES

The main MIST diesel storage tank was filled before fumigation testing so that the diesel-fuel characteristics were consistent throughout the test. The characteristics of the diesel fuel used in the calculations are provided in table I (ref. 3).

The gases used had low- and medium-energy contents. Because it was not practical to capture gas from operating plants, synthesized and bottled gas mixtures were purchased from the 3M Company for this test. The gas formulas are representative of various types of processes that produce this type gas.

The three gases used for testing had lower heating values of 6.11 MJ/m^3 (164 Btu/ft^3), 18.1 MJ/m^3 (485 Btu/ft^3), and 18.8 MJ/m^3 (505 Btu/ft^3), respectively, at standard conditions. Heating values of the gaseous mixtures were computed (ref. 4). The volumetric fractions of individual gases are multiplied by their respective heating values, and the sum of the products is the heating value of the mixture. Heating properties are given in table II, and characteristics of the three gases are presented in table III. Table IV contains information relative to the gas bottles that were required for gas quantity calculations.

ENGINE TEST PERFORMANCE

Test results show that low- and medium-energy gases may be used very efficiently to supplement diesel-fuel consumption. Because some air (scavenge air) is passed through the engine without being used in the combustion process and because of the inert nature of some gas components, it was initially assumed that more gas energy would be consumed than diesel energy saved. Table V shows that for gases 1 and 3, this assumption was not valid. The term "utilization efficiency" may be a misnomer here because test data show that, during fumigation, more gas was used than injected. The percentage of diesel-fuel reduction as opposed to gas energy for one series of 230-kilowatt test points is shown in figure 6. When these items are equal in value, the gas energy replaces diesel oil at 100-percent utilization efficiency. Various constant-utilization lines are shown for reference. When presented in either manner, gas 3 is the most efficient for fumigation and is followed by gas 1. No definite engine load point or injection percentage advantages could be determined from test data except that at higher loads and high (20 percent) fumigation rates, the percent savings were slightly higher.

Because no indication of detrimental engine operation could be found, a series of tests, including all loads and percentages, was completed, although gas utilization was much better than predicted. The engine head was then removed, and internal components were inspected visually for indications of pitting, etc. Nothing abnormal was found. The head was then cleaned and modified to accommodate a pressure transducer, as recommended by the engine manufacturer, for observing cylinder pressures. The operating cylinder-pressure testing is schematically defined in figure 7.

Although the second series of tests was conducted in the same manner as the first, even better results were obtained. Polaroid pressure traces were made with a storage oscilloscope at each test point. Neither detonation nor unusually high cylinder-pressure profiles were ever observed. Slight increases in operating pressures were noted, however, and, in general, pressure seemed to increase with percent injection. Example pressure traces are included as figure 8. Cylinder-pressure profiles for the three gases tested were all very similar to those for gas 1 (fig. 8) and are within the limits of the profiles shown.

The conclusions reached from the fumigation tests are as follows: (1) at least 20 percent of the diesel-fuel consumption may be supplemented by solid-waste-derived gas, (2) the overall engine-fuel efficiency may be improved by as much as 4 percent, and (3) engine operation was stable at all loads and gas injection rates and with each of the gases tested. The method of determining percent injection by monitoring throttle position proved to be very repeatable.

ERROR ANALYSIS

Because test results were so favorable, all areas were examined in which errors in measurement, techniques, or assumptions could have occurred. Operator

methods, meters, etc., have been evaluated to quantitate the error involved in individual data points. The sight-gage diesel-fuel measurement was accurate to one-tenth of a division. For a 5-minute test, this degree of accuracy amounts to approximately ± 0.527 megajoule out of 69.6 megajoules (± 500 British thermal units out of 66 000 British thermal units) at the 60-kilowatt test point. The amount of gas used was calculated from delta pressures and temperatures as previously explained. The pressure meter used was accurate to $\pm 34.5 \text{ kN/m}^2$ ($\pm 5 \text{ psi}$); i.e., for a constant temperature, the amount of gas used could be determined to approximately ± 0.264 megajoule (± 250 British thermal units) per bottle for the lowest energy gas for this worst-case situation.

DISCUSSION AND RECOMMENDATIONS

No similar previous studies could be located, with the exception of the Hamilton-Standard test discussed earlier, which was conducted using an open-combustion-chamber engine. Because the resulting data were significantly different, the results of this test can only be correlated with theoretical results that can be found in such publications as E. F. Obert's "Internal Combustion Engines."¹

The findings, based on results of the two test series, are as follows.

1. Total fuel consumption in precombustion diesel engines can usually be decreased slightly by fumigation.
2. Diesel-fuel consumption may be decreased by as much as 20 percent without detrimental engine performance (by precombustion or detonation).
3. Exhaust and other engine temperatures remain essentially constant (no difference in heat recovery).

The most important factor to be considered is that existing engines can utilize gas generated from solid waste as a fuel without major modifications to the engine. The utilization of this gas can substantially reduce diesel-fuel consumption and thereby extend the life of existing petroleum reserves. It is proposed that an intensive investigation be undertaken in the following areas of fumigation of diesel engines.

1. Effect of combustion-chamber design on the percent utilization of low- and medium-energy gases
2. Optimum percentage of gas that can be injected
3. Injection timing using pyrolysis gas

¹E. F. Obert, "Internal Combustion Engines" (third ed.), International Textbook Co. (Scranton, Pa.), 1968.

4. The use of lower grade fuel oil
5. Possible long-term effects detrimental to engine operation

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, September 17, 1976
647-10-00-00-72

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3. Standard Practices for Low and Medium Speed Stationary Diesel and Gas Engines. Sixth ed., Diesel Engine Manufacturers Association (New York, N.Y.), 1972.
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REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

TABLE I.-- CHARACTERISTICS OF DIESEL FUEL (EXXON)

Type	2-D
Gravity (American Petroleum Institute)	36
Sulfur content, p/m	0.18
Flash point, K ($^{\circ}$ F)	347.05 (165)
Pour point, K ($^{\circ}$ F)	255.38 (0)
Viscosity, 310.94 K (100 $^{\circ}$ F), SUS	35
Higher heating value, typical, MJ/m ³ (Btu/gal)	38 493 (138 200)
Specific gravity	0.8448
Density, kg/m ³ (lb/gal)	842.9 (7.034)
Lower heating value (ref. 3, p. 127), MJ/kg (Btu/lb)	43 (18 410)
 Test tank:	
No. divisions for 0.008 m ³ (2 gal) of fuel	21.45
Constant	0.6558

TABLE II.-- HEATING PROPERTIES OF FUEL GASES

Gas	Thermal energy, MJ/m ³ (Btu/ft ³) (net)
Hydrogen	10.2 (274.9)
Nitrogen	0 (0)
Carbon dioxide	0 (0)
Carbon monoxide	12.0 (321.6)
Methane	34.1 (914.5)
Ethane	61.0 (1639)
Ethylene	56.4 (1514)

TABLE III.- TEST GAS PROPERTIES

Gas	Volume, percent	Lower heating value, MJ/m ³ (Btu/ft ³)	
Gas 1			
Ethane	1	0.61	(16.39)
Ethylene	11	6.20	(166.54)
Methane	19	6.47	(173.75)
Hydrogen	25	2.56	(68.72)
Carbon dioxide	19	0	(0)
Carbon monoxide	25	2.99	(80.4)
Total		<u>18.83</u>	<u>(505.80)</u>
Gas 2			
Ethylene	1	0.56	(15.14)
Methane	1	.34	(9.14)
Hydrogen	16	1.64	(43.98)
Carbon dioxide	4	0	(0)
Carbon monoxide	30	3.59	(96.48)
Nitrogen	48	0	(0)
Total		<u>6.13</u>	<u>(164.74)</u>
Gas 3			
Carbon dioxide	47	0	(0)
Methane	53	<u>18.1</u>	<u>(485)</u>
Total		<u>18.1</u>	<u>(485)</u>

TABLE IV.- GAS CONSTANTS

[Bottle volume, 0.04384 m³ (2675 in³)]

Constant R	Volume, m ³ (stdft ³)	Pressure, MN/m ² (psig)	Temperature, K (°F)	Density, kg/m ³ (lb/ft ³)
Gas 1				
69.1006	4.45 (157)	10.3 (1500)	294.26 (70)	0.927 (0.0579)
Gas 2				
63.29	4.42 (156)	10.3 (1500)	294.26 (70)	1.01 (0.0631)
Gas 3				
52.95	2.94 (104)	6.9 (1000)	294.26 (70)	1.22 (0.0760)

TABLE V.- AVERAGE UTILIZATION EFFICIENCY

Fumigation, percent	Efficiency, percent		
	First series	Second series	Average
Gas 1 (18.8 MJ/m^3 (505 Btu/ft^3))			
20	99.5	106	102.8
15	90.9	112	101.5
10	110.2	108	109.1
5	<u>91.06</u>	<u>97.5</u>	<u>94.3</u>
	^a 98	^a 105.9	^b 101.9
Gas 2 (6.11 MJ/m^3 (164 Btu/ft^3))			
20	76	89.8	82.9
15	80	83.3	81.7
10	82	79.5	80.8
5	<u>65</u>	<u>85.8</u>	<u>75.4</u>
	^a 76	^a 84.6	^b 80.2
Gas 3 (18.1 MJ/m^3 (485 Btu/ft^3))			
20	122	104	113
15	102	111.8	106.9
10	105	108.4	106.7
5	<u>82</u>	<u>106.1</u>	<u>94.1</u>
	^a 103	^a 107.6	^b 105.2

^aSeries average.^bOverall average for first and second series.

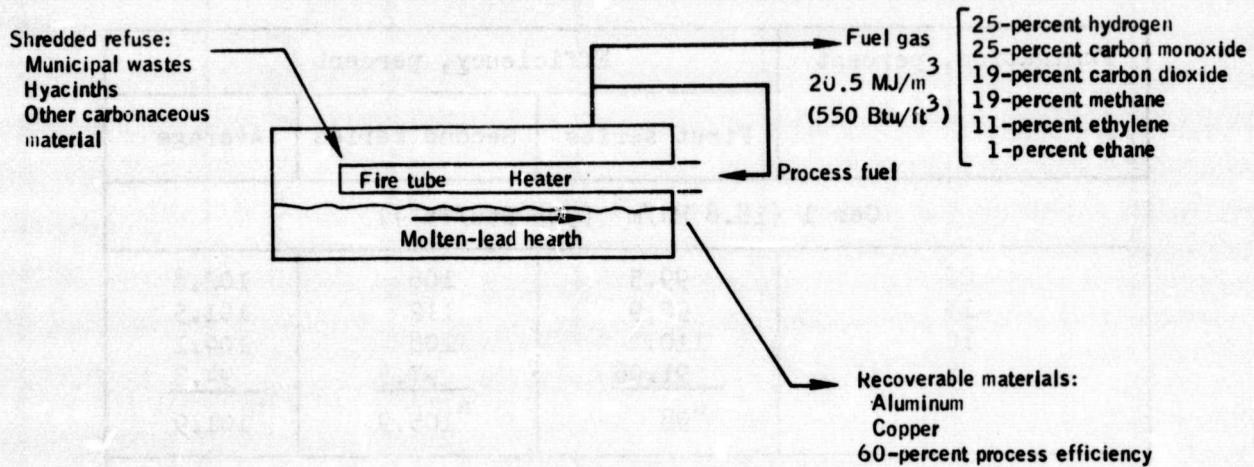


Figure 1.-- Barber-Colman pyrolysis process schematic.

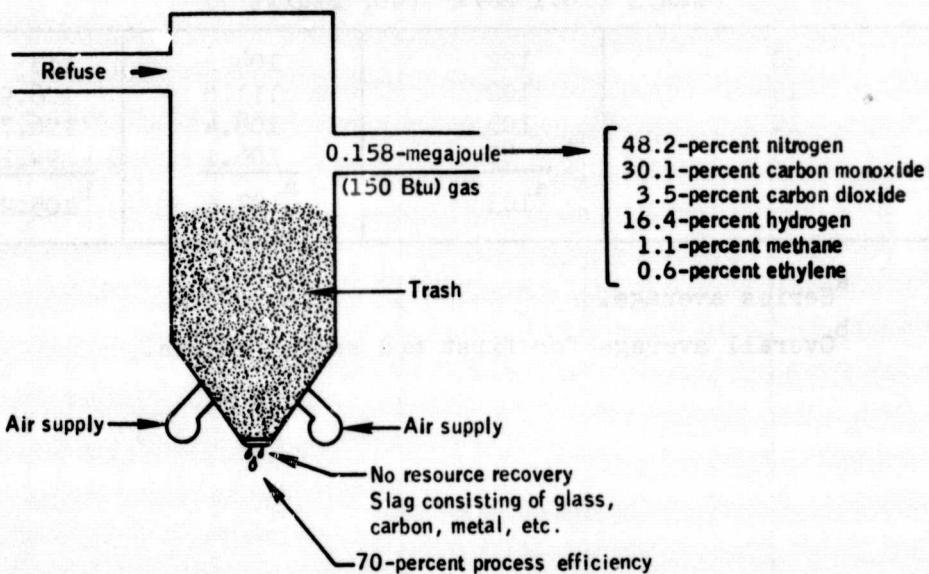


Figure 2.-- Hamilton-Standard fixed-bed gasifier schematic.

- Procedure**
1. Adjust minimum rack to 0 volt with null.
 2. Adjust maximum rack to 10 volts with gain.
 3. Set rack to 2.17 volts.
 4. Adjust null to 0 volt.
 5. At maximum rack, adjust gain to 1.31 volts; minimum rack should be 0.361 volt.

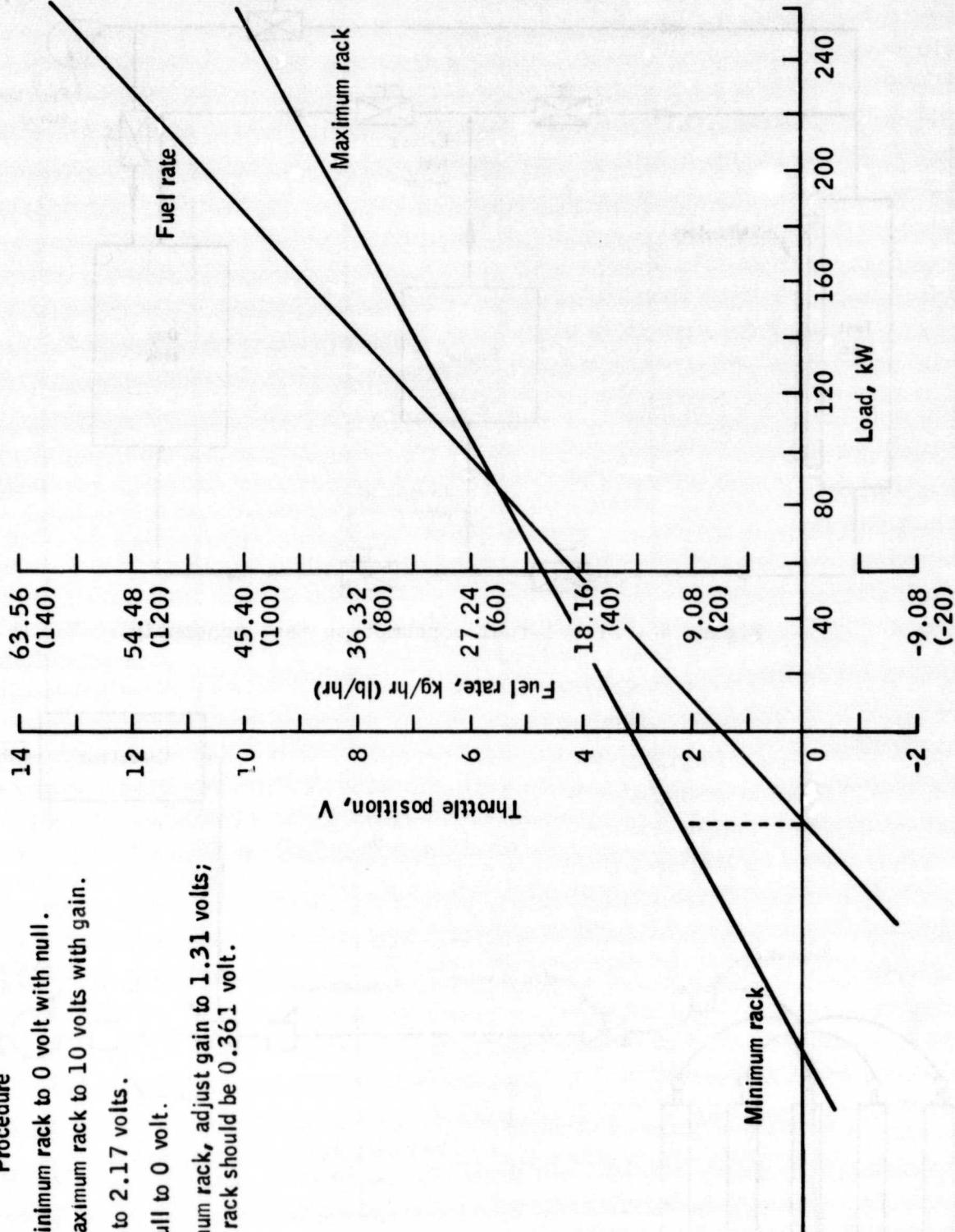


Figure 3.- Throttle position as a function of load.

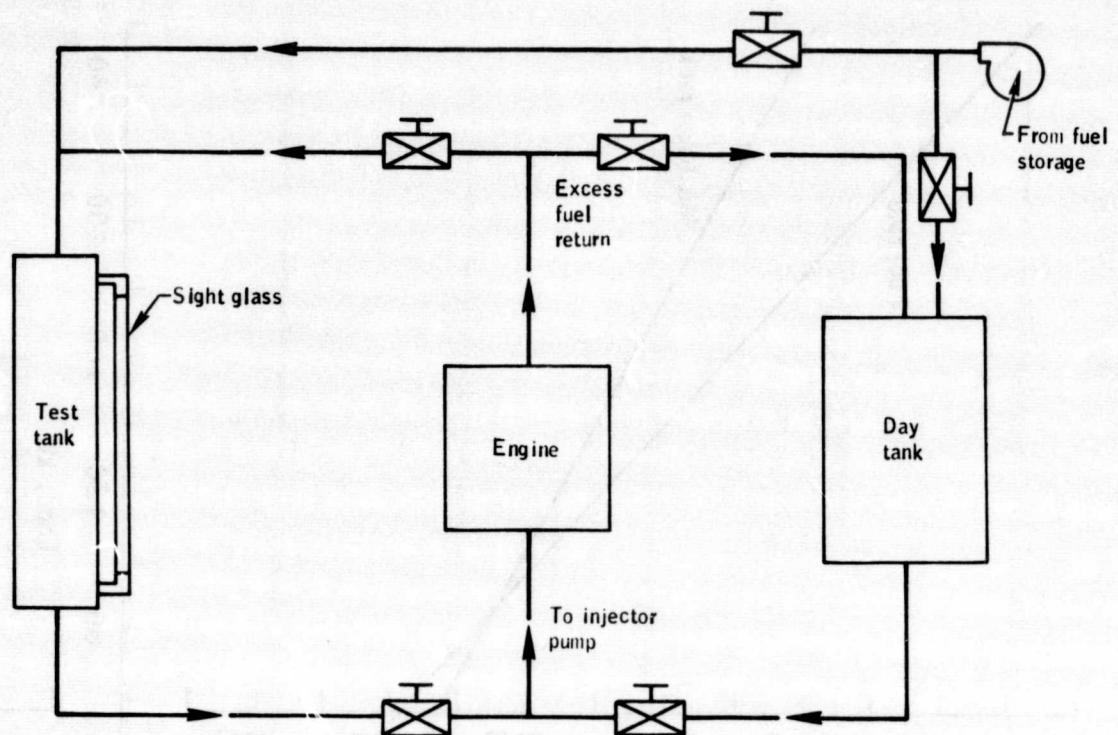


Figure 4.- Diesel-fuel consumption test schematic.

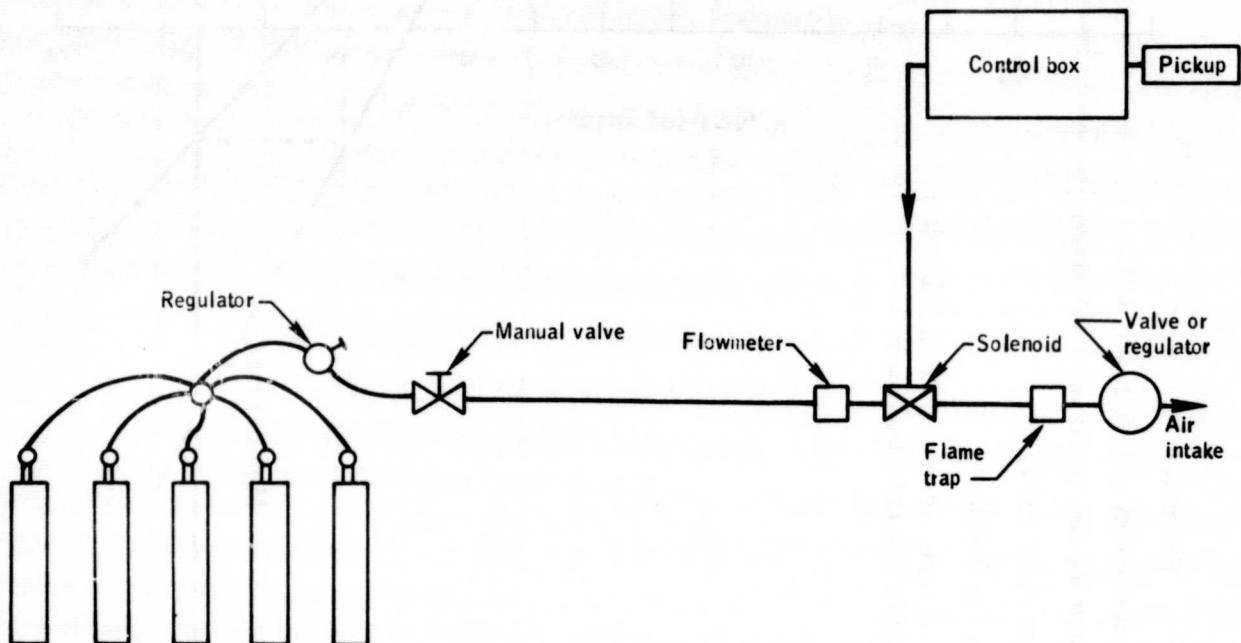


Figure 5.- Fumigation test schematic.

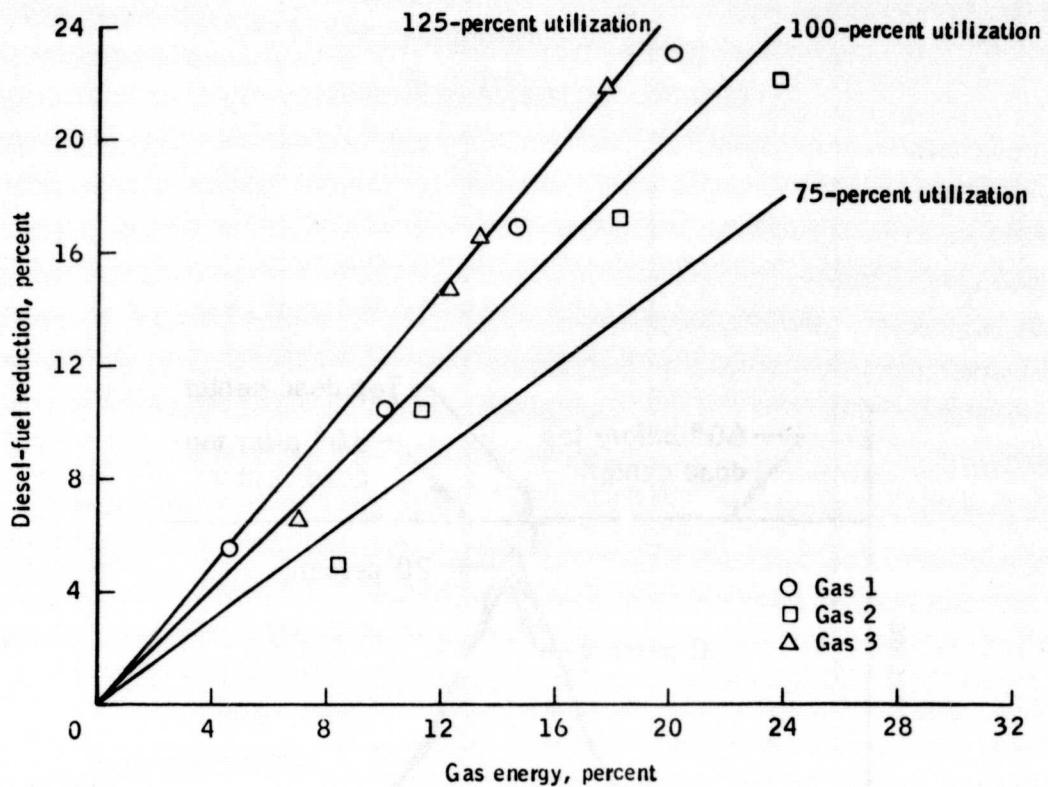


Figure 6.- Diesel-fuel reduction as opposed to gas energy at 230 kilowatts.

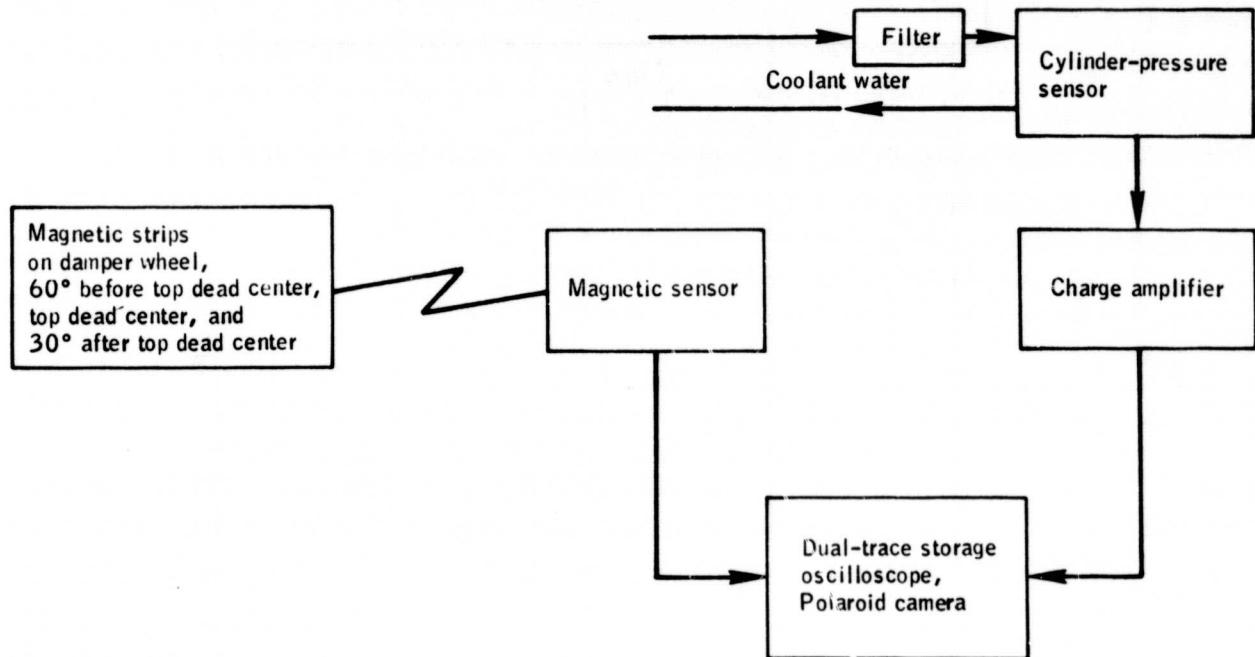


Figure 7.- Detonation and operating pressure testing diagram.

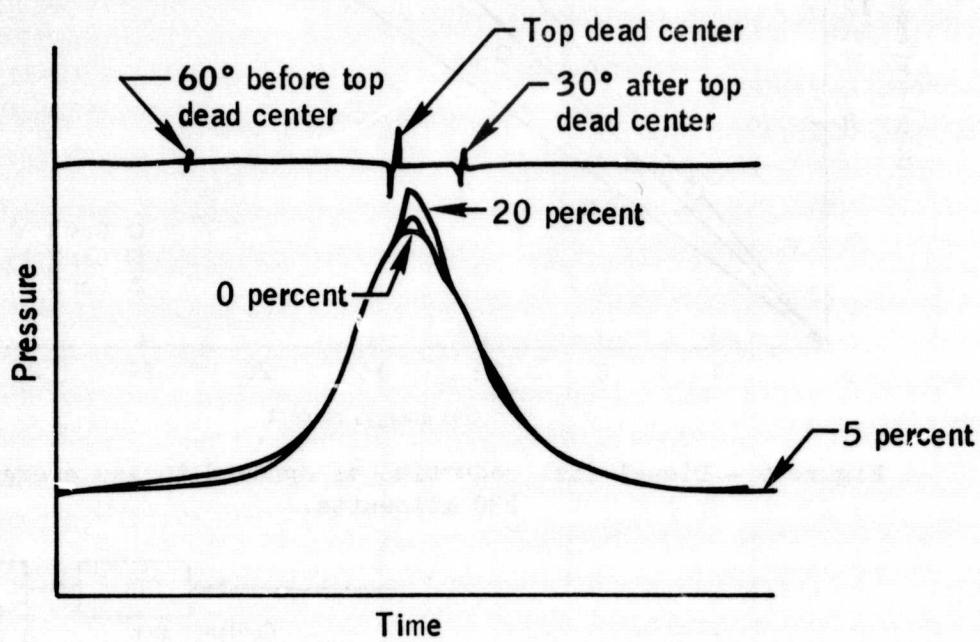


Figure 8.- Cylinder-pressure variation for gas 1 at
230 kilowatts.